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Authors: Wagle, Nisha, Dhakal, Madhav P., and Shrestha, Arun B.

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Adaptation Strategies to Address Challenges of Traditional Agricultural Water Management in the Upper Indus Basin

Nisha Wagle**, Madhav P. Dhakal, and Arun B. Shrestha
**Corresponding author: nisha.wagle@icimod.org*

International Centre for Integrated Mountain Development (ICIMOD), GPO Box 3226, Kathmandu, Nepal

Agriculture in the Upper Indus Basin largely depends on the cryosphere, and cultivation is possible only through irrigation. The agriculture system, however, faces challenges in terms of climate, extreme events, water scarcity, and other socioeconomic conditions. Hence, a scoping review was conducted to identify the irrigation systems and coping mechanism in the 4 valleys of the basin. Centuries-old irrigation canals, water distribution, management systems, and coping mechanisms are in place. Adaptation strategies are managed by communities, and some are established and supported by government and development organizations. Successes, in terms of increased income, crop yields, and cost, are widely reported; however, evidence of their efficiency and sustainability is scarce.

Keywords: *irrigation practices; agriculture; climate change; water scarcity; adaptation strategy; high mountains.*

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Introduction

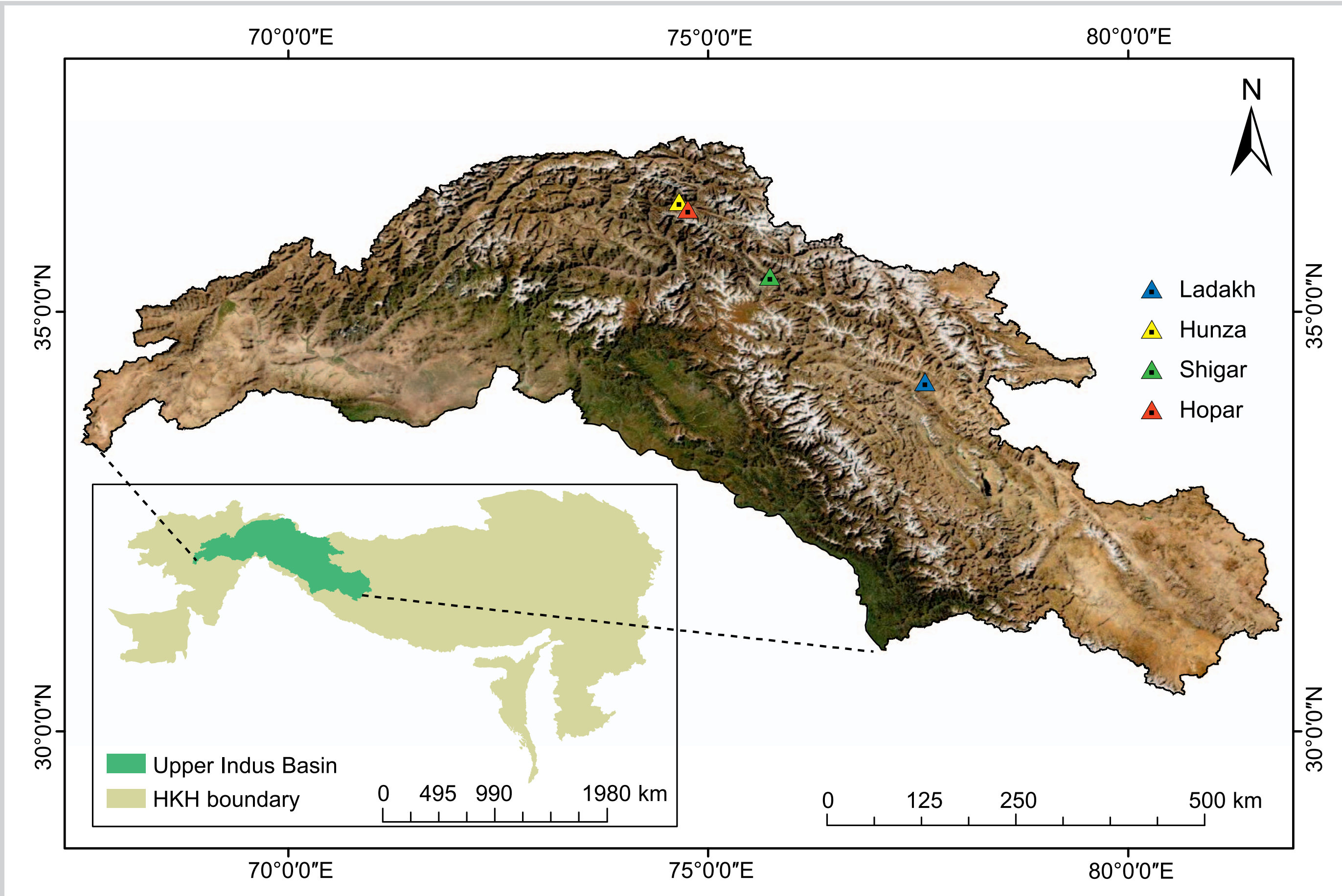
The high mountains of the Hindu Kush Himalaya (HKH) are home to about 1.9 billion people, who are dependent on water resources (Sharma et al 2019). The Indus, Ganges, and Yangtze rivers, fed by glacier and snow melt, contribute significantly to irrigation, hydropower, drinking water, and livelihood activities (Scherler et al 2011; Riaz et al 2014). However, meltwater contribution varies among the basins. Dependency of the Indus on meltwater is high, as it receives large snowfalls in winter due to westerlies. In contrast, the eastern region (Ganges) is monsoon dominated (Lutz et al 2014; Krishnan et al 2019). This study focuses on the Upper Indus Basin (UIB), which is the area above the Tarbela dam in the Indus basin (Mukhopadhyay and Khan 2015).

Glacier and snow melt play a pivotal role in sustaining life; they are the only source of irrigation and domestic water in UIB (Shaheen et al 2013). For example, 95% of the total cultivated area in northern Pakistan is irrigated using this water (Velde 1989). The system is centuries old and unique (Scott et al 2019) in benefiting from the cryosphere (Mukherji et al 2019). It is a complex sociohydrological system, where the physical environment and socioeconomic activities shape the irrigation infrastructures and basic water use regulations (Kreutzmann 2011; Nüsser et al 2012; Parveen et al 2015; Nüsser and Baghel 2016). Although the cryosphere contributes to essential services, these services are also influenced by factors such as harsh climatic conditions, climate change, extreme events, and hazards (Parveen et al 2015; Nüsser, Dame, Kraus, et al 2019; Nüsser, Dame, Parveen, et al 2019). Among these, climate change is prominent, with warming and glacier mass reduction being reported (Shean et al 2020). For example, a third of the ice mass is projected to be lost by 2100 in Asia's high mountains if the temperature increase is kept at 1.5°C (Kraaijenbrink et al 2017). In the UIB, warming by 5°C by 2100 is projected under the 8.5 representative concentration pathway (Forsythe et al 2014; Huang et al 2017), impacting the glaciological and hydrological cycle and melt-fed irrigation systems (Hock et al 2019). In addition, the frequency of extreme events will likely increase in the region (Wijngaard et al 2017).

Adaptation in agriculture depends on climate, biophysical, sociopolitical, and environmental conditions. In recent years, farmers have adapted to climate change through technological innovations (Karki and Gurung 2012). In the basin, adaptation in agriculture is based on local indigenous knowledge and incorporates context-specific procedures (Parish 1999; Parveen et al 2015; Clouse et al 2016; Nüsser, Dame, Kraus, et al 2019; Nüsser, Dame, Parveen, et al 2019). However, it is impacted by the limited financial and technical capacity of the developing countries (Karki and Gurung 2012). This study focuses on adaptation strategies for meltwater-dependent irrigation, which aligns with the definition from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, "The process of adjustment to actual or expected climate change and its effect" (Noble et al 2014: 838).

Adaptation in agriculture is crucial in sustaining lives and livelihoods; hence its assessment can provide a basis for informed decision-making and planning for the future. Our aim was to synthesize relevant information using a scoping

FIGURE 1 Upper Indus Basin boundary with the location of the study area.



review methodology. We selected 4 study areas with similar climatic conditions, with the assumption that this represents the entire basin. The main aim of the study was to identify the irrigation systems and water distribution and allocation mechanisms, challenges, and adaptation strategies, their benefits, and their scaling out. This paper does not cover the knowledge gaps, which is a limitation of the study. The paper is divided into a method section, describing the study area and methodology; area-wise results on traditional irrigation and its management, challenges, and adaptation measures; and a discussion and conclusion.

Methods

Study area

The UIB (385,000 km^2) consists of heavily glaciated and barren high mountains, with snow and ice covering about 20,000 km^2 (Lutz et al 2014). The high-elevation, cold upstream areas, along with high winter precipitation due to westerlies, result in persistent snow cover in the basin. The Ladakh, Hunza, Shigar, and Hopar valleys were selected for this study, as shown in Figure 1.

Ladakh is located at 3000–5500 masl and has a population of 133,487 (GoI 2011). It receives low annual precipitation of 115 mm and has an annual mean temperature of 7.3°C at Leh (Thayyen et al 2013; Chevuturi et al 2016). Hunza is located between 2400–2800 masl with a population of 20,000 (as of 2010) (Parveen et al 2015). The annual precipitation is 731 mm (Shrestha and Nepal 2019), and the average temperature is 11°C at Aliabad. Shigar is located between 2300–3050 masl (Hill 2014a) and has an average annual temperature of 0.1°C and receives 993 mm annual precipitation (https://en.climate-data.org/info/sources/). Hopar has a population of about 4000 people. The average annual precipitation is >130 mm at elevations below 3500 masl (MacDonald 1989).

Methodology

Scoping reviews help to systematically map the literature available, identify key concepts, evidence, and gaps (O'Brien et al 2016). There is no defined methodology for a scoping review, so we followed the framework of Arksey and O'Malley (2005). The research questions were the following:

1. What are the characteristics of the traditional irrigation systems and their management?
2. What challenges are faced by those systems?
3. What adaptation strategies have been adopted to secure irrigation water and ensure their effectiveness and sustainability?

SCOPUS and Google Scholar were searched using probable keywords, logical operators, and filtering techniques (Table 1), resulting in 224 and 960 articles, respectively. These were reviewed thoroughly based on inclusion criteria, research questions, and relevance. The

TABLE 1 Search criteria.

Database	Choice of keywords	Remarks
Scopus®	(TITLE-ABS-KEY("Upper Indus Basin" OR "Askole" OR "Hunza" OR "Shigar" OR "Ladakh" OR "Hopar" OR "Karakoram")) AND (TITLE-ABS-KEY (irrigation OR agriculture)) OR (TITLE-ABS-KEY (adaptation OR management OR mitigation OR measures OR coping OR intervention)) AND (LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "AGRI")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "ch") OR LIMIT-TO (DOCTYPE, "cp") OR LIMIT-TO (DOCTYPE, "re") OR (EXCLUDE (DOCTYPE, "no")) AND (EXCLUDE (PUBYEAR, 2020)) AND (EXCLUDE (PUBYEAR, 1979))	224 articles
Google Scholar	("Upper Indus Basin" OR "Askole" OR "Hunza" OR "Shigar" OR "Ladakh" OR "Hopar" OR "Karakoram") AND ("Irrigation" OR "Agriculture") AND ("Adaptation" OR "Intervention" OR "Coping" OR "measures" OR "artificial glacier" OR "pump" OR "ice stupa" OR "glacier melt" OR "snowmelt" or "river water")	960 articles

inclusion criteria were (1) study conducted in the UIB; (2) articles written in English; (3) peer-reviewed articles and organizational reports (retrieved from himaldoc.org); (4) a focus on adaptation in agriculture; and (5) articles published after 1980. Finally, 39 nonduplicated papers, of which 3 cover 2 study areas, were selected for detailed review (Table 2). All relevant information was noted and analyzed qualitatively.

Results

Traditional irrigation system and its management

Agriculture in UIB is mostly dependent on irrigation. Water is diverted from snow and glaciers in all study areas; in addition, river water is used in Ladakh and Shigar, and spring water in Shigar (MacDonald 1998; Schmidt 2004; Dame and Nüsser 2011; Nüsser et al 2012; Hill 2017). Many irrigation canals are centuries old, and new ones have been established in recent decades to cater for increasing demand (Sidky 2008; Schmidt 2004). The system is traditional technology incorporating sociocultural and technical components (Gupta and Tiwari 2002). Water is diverted to the valleys through canals along the mountain slopes (Scott et al 2019); the diversion is dependent on geographical location. Though similar, the irrigation systems differ in terms of irrigated areas, the rules for water allocation, distribution, and maintenance. These differences are shaped by factors such as topography, glacier size, water availability, temperature, soil type, and seepage. Details of the study area are discussed below.

Ladakh: In Ladakh, there are 2 types of gravity-controlled irrigation (Nüsser et al 2012). The first uses meltwater, and the second extracts water from the Indus River, which depends on inter- and intra-annual water availability (Nüsser et al 2012). In the first type, meltwater drained into a stream (*tokpo*) is diverted to the canal network, called *yuras/sub-yuras* (Dawa et al 2000; Gupta and Tiwari 2002), which is built along the mountainside and lined with clay to hold the water. For instance, there are 59 main canals in Domkhar village, some crossing the valley (Takeda and Yamaguchi 2015). Another method is to allow the water to freeze in the fields to enable soaking in winter; this is followed by plowing in spring (Shaheen et al 2013; Takeda and Yamaguchi 2015). Storage ponds (*zings*) and reservoirs are also used to store the excess water for irrigation (Dawa et al 2000).

The water distribution system is called *chures* or *bari*. It is recorded in an official document (*riwaj-e-apashi*) and regulated by community water managers (*chudpon*) (Dawa et al 2000; Hill 2014a; Norphel and Tashi 2015; Nüsser, Dame, Kraus, et al 2019). The distribution in small villages (*phey*) is done by households themselves, while a lottery system is practiced in other villages (Gupta and Tiwari 2002; Angchok and Singh 2006). There is no defined allocation system in water access areas (Takeda and Yamaguchi 2015). Villagers construct and maintain ponds and ice reservoirs (Angchok et al 2006; Nüsser et al 2012; Nüsser, Dame, Kraus, et al 2019).

Hunza: Hunza has a complex indigenous traditional irrigation system, which began in AD 1780 when water was diverted from the Batura glacier to Passu village (Parveen et al 2015). Here meltwater is channeled to the arable land, creating "irrigation oases" (Gioli et al 2014). Irrigation canals (*kuhls*) were developed using local resources and engineering technology. These were upgraded and extended under several rulers (Dani and Siddiqi 1986; Velde 1989); for example, a large-scale irrigation system was established during the Mir Silim regime (AD 1790–1824) (Sidky 2008). A water management committee schedules the distribution (*nobat*) of water; however, water use rights are disputed among new in-migrants and original settlers. Households follow a maintenance schedule (Parveen et al 2015). In Aliabad, flow is supervised at regulatory gates by watchmen (Dani and Siddiqi 1986).

Shigar: In Shigar, gravity flow offtake irrigation systems divert water from snow, glaciers, and springs, and, less commonly, rivers (Hill 2014b, 2017). Water is diverted from a large stream (*nalla*), locally called *Hrkong* or *Hrka*. Here water is allocated according to the number of households with land under the canal command area. In Niesolo village, villagers use the *Hamidasi lungma* canal first, and households with land under the canal area take turns every 15 days (Hill 2017). For irrigation, the *riwaj-e-apashi* (official document) acts as a guideline, and oral regulations are also applied (Hill 2012, 2014a, 2014b). In earlier times, the *nambardar* (intermediary position between farmer and government) maintained the system, but nowadays elders look after irrigation-related affairs (Hill 2017). In addition, a person from each household repairs the canal on their return from a camping trek in May (Schmidt 2004; Hill 2014a, 2014b).

Hopar: In Hopar, a 300-km-long canal (*Nala*) has diverted melt water since 1986 (Butz 1987, 1989). Cultivation is

TABLE 2 Study locations of reviewed literature.

Valley, country (no. references)	References
Ladakh, India (21)	Angchok and Singh 2006; Clouse 2014, 2016, 2017; Clouse et al 2016; Dame and Nüsser 2011; Dawa et al 2000; Gupta and Tiwari 2002; Hasnain 2012; Hill 2014a, 2014b; Norphel and Tashi 2015; Nüsser et al 2012; Nüsser and Bhagel 2016; Nüsser, Dame, Kraus, et al 2019; Nüsser, Dame, Parveen, et al 2019; Shaheen 2016; Shaheen et al 2013; Sharma 2019; Sudan and McKay 2015; Takeda and Yamaguchi 2015
Hunza, Pakistan (12)	Ashraf et al 2012; Dani and Siddiqi 1986; Dhakal et al 2021; Gioli 2014; ICIMOD 2017; Kreutzmann 2011, 2012; Nüsser, Dame, Parveen, et al 2019; Parish 1999; Parveen et al 2015; Sidky 2008; Velde 1989
Shigar, Pakistan (6)	Hill 2012, 2014a, 2014b, 2017; MacDonald 1989; Schmidt 2004
Hopar, Pakistan (3)	Butz 1987, 1989; Spies 2016

carried out on mountain slopes above the terrace. In Shishkin village, 2 water canals divert water from a stream fed by supraglacial meltwater (Spies 2016). Here villagers carry out necessary maintenance (Butz 1987).

Challenges to the irrigation system

In the study area, flash floods, landslides, riverbank erosion, glacier lake outburst floods (GLOFs), sedimentation, periodic avalanches, and warming-induced melt, together with turbulent/variable flow, low temperatures, and water shortages are prevalent (Butz 1987, 1989; MacDonald 1989; Shaheen et al 2013; Parveen et al 2015; Clouse et al 2016; Hill 2017; Nüsser, Dame, Kraus, et al 2019; Scott et al 2019). Climate change exacerbates the melt process, intensifies the water shortage, impacts the snow/glacier-fed irrigation system (Parveen et al 2015; Nüsser et al 2018; Nüsser, Dame, Kraus, et al 2019), and increases the frequency of hazards. In addition, other administrative and socioeconomic challenges have frequently hampered the operation of the irrigation system. The site-specific challenges (Table 3) are discussed in detail below.

Ladakh: In Ladakh, delayed melt and water scarcity in spring have hampered efforts to restore traditional ponds, reservoirs, and *kuhls* (Shaheen et al 2013). In addition, frequent freezing, erosion, and sedimentation impact the flow in the canal diverting water from the ice reservoir. Recurrent floods have reduced the functionality of the ice reservoir, leading to it being abandoned, which impacts the agricultural land (Nüsser, Dame, Kraus, et al 2019). An irrigation project and artificial glaciers were impacted by the 2006 flash floods and 2010 mudslide, respectively (Norphel 2012; Nüsser et al 2012). In addition, competing seasonal labor requirements, better off-farm job opportunities, and the reduced importance of farming are other challenges (Nüsser, Dame, Kraus, et al 2019).

Hunza: In Hunza, GLOFs from the Batura glacier and recurring floods from the Shimshal River have eroded agricultural lands in Passu village. The advancing glacier during the 19th century destroyed the cropland (Parveen et al 2015). In 2008, 5 GLOFs in Passu destroyed the Passu main and Murabadad canals (Dhakal et al 2021); downwasting impacted the water transfer scheme (Nüsser, Dame, Parveen, et al 2019), and inundation of Attabad Lake affected millions on the irrigated plains (Kreutzmann 2012). Likewise, erosion in 2009 and 2011 destroyed canals in Passu. In 2015 floods, debris flow, and streamflow erosion damaged all irrigation canals in Moorkhun village (Dhakal et al 2021). In addition, labor- and capital-intensive irrigation networks are major hurdles (Parveen et al 2015; Nüsser, Dame, Parveen, et al 2019).

Shigar: Water availability varies over the year due to climate change, and water shortages are frequent (Hill 2012, 2014b, 2017). Landslides, frost, and windstorms also hamper irrigation (MacDonald 1998). In addition, administrative issues, such as financial and labor crises, are prevalent (Hill 2014a, 2014b).

Hopar: In Hopar, glacier retreat and frequent slumping of moraines have halted canal reconstruction and ended farming. Glacier-fluctuation–induced erosion, flooding, and landslides have impacted agricultural land, and inconsistent melt disrupted the *Nala* (Butz 1987; MacDonald 1989). For example, meltwater decline has resulted in a barren area in

TABLE 3 Summary of challenges to the irrigation system faced in study locations.

Study area	Climate change/natural hazards	Water scarcity	Administrative
Ladakh	Riverbank erosion and sedimentation, Snow and glacier freezing, Flash floods, Landslides	Shortage in spring season	Seasonal labor shortages due to better off-farm opportunities
Hunza	Glacier lake outburst floods, Flash floods, Glacier fluctuations, Erosion and sedimentation	Seasonal water scarcity	Financial resource crisis, Labor shortage
Shigar	Erosion, Landslides, Frost, Windstorms	Frequent water shortages	Financial resource crisis, Labor shortage
Hopar	Glacier fluctuation-induced floods, Erosion and landslides, Sedimentation, Avalanches, Variable and turbulent flow, Low temperature	Seasonal water scarcity, Timing uncertainty	Financial resource crisis, Labor shortages

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TABLE 4 Summary of adaptation measures in villages studied.

Study area	Adaptation strategies
Ladakh	Diversion canals (traditional)
	Ice reservoirs (artificial glacier, ice *stupa*, snow barrier) (recent)
	Zings (traditional)
	Snow harvesting (traditional)
Hunza	Migration to new sites (traditional)
	Drought-tolerant plants (recent)
	Intake relocation (traditional)
	Preservation/redevelopment of agricultural land (traditional)
	Replacement of damaged canals with pipelines (traditional)
	Riverbank stabilization to protect intakes (traditional)
	Meltwater storage (traditional)
	Sedimentation/stilling basin (traditional)
	Canal construction (traditional)
	Solar pump and hydraulic ramp pump (recent)
Shigar	Canal, reservoir, and tunnel construction and renovation (traditional and recent)
	Zing (traditional)
	Pipe and lift irrigation projects (recent)
Hopar	Flow regulation by adjusting dam density, construction of sluices (traditional)
	Retaining walls for canal protection (traditional)
	Vegetation plantation for canal protection (traditional)
	Canals construction at a slope of 3° (traditional)
	Widen secondary channels to increase temperature and allow silt deposition (traditional)

Shiskin village, Maruk has never been cultivated due to water shortages, and farmers in Shaltar abandoned fields due to difficulties in accessing the landslide-prone slope (Spies 2016). Turbulent flow, low temperatures, and higher sediment load also hampered the system (Butz 1987, 1989).

Adaptation strategies

Autonomous adaptation is crucial in HKH. This is based on local knowledge of traditional management practices (Mishra et al 2019). Adaptation in agriculture is essential in the region, where rainfed agricultural production is not possible (Shaheen et al 2013). Adaptive techniques and interventions, mainly autonomous and reactive (Table 4), established by communities and other developmental organizations are discussed in detail below.

Ladakh Region: In Ladakh, artificial glaciers have a long tried-and-tested history of providing water during the agricultural season (Hasnain 2012; Nüsser et al 2012; Clouse 2014, 2016; Nüsser, Dame, Parveen, et al 2019). This represents the coevolution of environmental processes and local livelihoods under a sensitive sociohydrological system. Increased irrigation frequency, yield, soil moisture, and groundwater recharge and fewer water use restrictions are among the benefits observed. For example, villagers in Nang and Igoo received economic benefits and improved their living conditions (Clouse 2014; Sudan and McKay 2015; Nüsser and Bhagel 2016; Nüsser, Dame, Kraus, et al 2019).

In 2014, ice *stupa* (similar to artificial glaciers), which grow into free-standing towers of ice, were established. These provide regular water throughout the year but are costlier and more labor intensive than artificial glaciers. They also require regular maintenance (Clouse et al 2016; Sharma 2019). Likewise, *zings* have been constructed to store excess water and are used during times of water scarcity (Gupta and Tiwari 2002; Nüsser et al 2012). Nüsser, Dame, Kraus, et al (2019) analyzed the efficacy of 14 ice reservoirs (including artificial glaciers, ice *stupa*, and *zings*) and defined them as a local technology that addresses water scarcity, not as a climate adaptive strategy. The snow barrier band is another technique, which directs and transplants snowfields from one watershed to next (Clouse et al 2016; Nüsser, Dame, Kraus, et al 2019). Pondwater is also regulated through a traditional way of blocking and releasing the water, as required, by using stones or old clothes (Angchok and Singh 2006).

Hunza Valley: In Hunza migration to safer areas and recovery and rehabilitation of barren lands after natural hazards were common. After the 1857 and 1960 floods, people migrated from Passu and cultivated barren land in another location (Kreutzmann 2012; Parveen et al 2015). Like in the UIB, land abandonment and migration were popular strategies in Nepal to avoid water scarcity (Chapagain and Bhusal 2013). People in Passu with limited resources were unable to migrate (Ashraf et al 2012). Migration and irrigation attempts on Suronobod terrace failed after the 1857 flood (Parveen et al 2015). Stilling basins were built to reduce the silt in *kuhls*, and drought-tolerant sea buckthorn and poplar trees were planted to protect the land from erosion (Velde 1990; Ashraf et al 2012; Parveen et al 2015). A shift to less water-intensive crops in Uttarakhand and use of improved crop varieties in Nepal also proved beneficial (Khanal 2014; Dhakal et al 2016; Mishra et al 2019). Construction of water reservoirs and ponds, maintenance of irrigation canals, and intake relocation were other strategies used to secure water. In Borith village, locals impound and divert water by blocking the gaps between the glacier and lateral moraines (Parveen et al 2015).

During the 1980s, canal extension by the Aga Khan Rural Support Program (AKRSP) increased cultivation in Passu and supplied water to 450 ha of land in Aliabad (Parish 1999; Parveen et al 2015). Recently, the International Centre for Integrated Mountain Development (ICIMOD) established solar and hydraulic ram pumps. The solar pumps are effective water conservation tools under climate change and are clean, economically feasible, and not labor intensive (Dhakal et al 2021). Their benefits include ease of use, increased income, and improved livelihood opportunities (ICIMOD 2017). The hydraulic ram pumps have increased productivity and provide an alternative to flood irrigation, requiring zero energy and being less labor intensive.

However, a few measures were ineffective due to glacier fluctuations, complex geology, labor intensive work, and lack of water availability. For example, the government's attempt to preserve and redevelop agricultural fields, irrigable land expansion and canal restoration by AKRSP in 1983–1984, intake relocation from Ghulkin to a supraglacier lake in the 1940s, and canal diversion across the lateral moraine (Parveen et al 2015; Nüsser, Dame, Parveen, et al 2019) all failed. In 2013 the AKRSP-funded pipeline in Borith, sourcing water from 2920 masl, failed due to the unavailability of water year-round at that elevation (Parveen et al 2015). Canal construction in Ganish village was disrupted by flooding, and a diesel pump was not operated due to disputes over ownership and land use rights as well as high fuel and maintenance costs (Parish 1999). The high magnitude of hazards also impacted the control of riverbank undercutting in Passu (Parveen et al 2015).

Shigar Valley: In Shigar, to cope with seasonal water variation, *zings* store overnight water. Villagers also sacrifice a calf in spring before bringing water; this is linked to the culture and perception that water was not available in 2004–2005 when they failed to sacrifice a calf (Hill 2012, 2017). The AKRSP and Social Economic and Environmental Development (SEED) initiated projects with water supply schemes, irrigation canals, and a reservoir (Hill 2014a, 2017). In 1990 a non-canal irrigation project (pipe, lift) was implemented by AKRSP, and in 2012 canal renovation and tunnel construction were carried out by SEED. However, the canal constructed in 1996 by AKRSP failed due to lack of maintenance (Hill 2012, 2014a, 2014b). In 2003 AKRSP established a *hrkong rgyamso* (irrigation system), which served 20–30 households, and a program for improvement of watercourses initiated 27 irrigation projects (Hill 2017).

Hopar Valley: The impact of floods, erosion, and slumping was reduced by watchmen, who regulated flow and diverted water to small canals, allowing flow to disperse (Butz 1987, 1989). Stone walls were constructed and plantations established to protect canals and prevent landslides. Canals were built at 3° slopes to reduce sedimentation and erosion (Butz 1989). Low water temperature was addressed by digging secondary canals to increase radiative and convective warming (Butz 1989).

However, construction of new irrigation canals in the next available melt water source, funded by AKRSP, failed due to underestimation of contingencies in the physical environment, and in Shishkin a canal failed due to leakage and a lack of maintenance. Debris, mudflows, and land slumping hampered efforts under the Kaushal Pakistan program to repair and widen canals. In addition, canal rehabilitation, pipe installation, and construction of a new and lower canal in Shaltar did not progress due to misuse of funds (Spies 2016).

Discussion and conclusion

In the UIB, irrigation is largely dependent on meltwater, which supports the local economy and livelihood. Traditionally, adaptation measures were carried out by communities, including governmental and nongovernmental institutions, and several improvements were made, including some recent interventions. Some of measures failed due to frequent hazards, administrative issues, and complex geography. This study reviewed measures to sustain agriculture, but their efficacy and sustainability from socioeconomic and environmental perspectives are lacking. Additionally, this study did not cover the knowledge gaps in adaptations of agriculture.

Lessons can be learned from the failed measures, and successful projects could be replicated or scaled up in similar settings, as climate change and associated hazards are likely to increase in the future (Wijngaard et al 2017). For example, solar pumps constructed for mountain-specific environments have been scaled out to 10 sites by the United Nations Development Programme, and the federal government plans to install 150 systems in 10 districts in Gilgit-Baltistan (Dhakal et al 2021). Although ice reservoirs provide temporary relief, they are sensitive to climate change and hampered by factors such as labor shortages, high costs, and funding availability (Nüsser et al 2012; Clouse 2014; Clouse et al 2016; Shaheen 2016; Nüsser, Dame, Kraus, et al 2019). The government and NGOs could provide advice with context-specific measures for the local population to cope with the challenges.

Active community participation and enabling conditions ensure sustainability and effectiveness as they cater for local needs, align with the culture, and increase acceptance. They also increase farmers' adaptation capacity, diversify finances and the workforce, and reduce uncertainty (Zhang et al 2018). They allow risks and benefits to be shared, community ownership, and resource distribution. They also reduce the government's burden, as showcased by AKRSP in Pakistan (Dani and Siddiqui 1986, Parish 1999). In the HKH region, local participation in adaptation planning and implementation is limited (Mishra et al 2019), including in government departments and integration with other organizations (Hussain et al 2018). Here actions such as climate-smart practices, infrastructure adjustments, and improved water harvesting are essential. Integrated water resource management could help to reduce water-induced risks.

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